

# BRANCHING FRACTIONS AND CP ASYMMETRIES IN $B \rightarrow H^+ H'^-$

GIOVANNI PUNZI

FOR THE CDF II COLLABORATION

*Scuola Normale Superiore and Istituto Nazionale di Fisica Nucleare*

*Via F. Buonarroti 2, Pisa, I-56100 Italy*

*E-mail: giovanni.punzi@pi.infn.it*

Relative branching fractions of  $B_{d,s} \rightarrow h^+ h'^-$  decays (where  $h, h' = K$  or  $\pi$ ) and direct CP asymmetry in  $B_d \rightarrow K^+ \pi^-$  have been measured with  $180 \text{ pb}^{-1}$  of data collected by the CDFII detector at the Tevatron collider. This includes the first BR measurement of a charmless  $B_s \rightarrow \text{PP}$  decay ( $B_s \rightarrow K^+ K^-$ ).

## 1 Introduction

The comparison of measurements performed on a number of such modes at  $e^+ e^-$  experiments with theoretical expectations has provided a wealth of information.

The CDF II experiment<sup>1</sup> has access to a large yield of these decays at the Tevatron collider, thanks to a dedicated trigger on secondary decay vertices. In addition, it is also sensitive to the corresponding decays of  $B_s$  mesons and beauty baryons, which provide much additional valuable information<sup>2,3</sup>. In particular, combining measurements of  $B_s$  modes with measurements on the  $B_u/B_d$  sector allows eliminating or constraining uncertain hadronic parameters.

In this paper we report on the analysis of 2-body charmless decays of  $B_d$ ,  $B_s$  and  $\Lambda_b$  in a sample of  $179 \pm 11 \text{ pb}^{-1}$  collected with the CDF II detector between February 2002 and September 2003.

## 2 Sample Selection

The data sample was selected in the 3-level CDF trigger system by a set of requirements dedicated to  $B \rightarrow h^+ h'^-$  candidates. Two oppositely-charged tracks are required, with  $p_T > 2.0 \text{ GeV}/c$ , total  $p_T > 5.5 \text{ GeV}/c$ , impact parameters larger than  $100 \mu\text{m}$ , and azimuthal opening angle between  $20^\circ$  and  $135^\circ$ . The  $B$  candidate is then required to have a

transverse decay length larger than  $200 \mu\text{m}$ , invariant mass between  $4.0$  and  $7.0 \text{ GeV}/c^2$ , and to point back to the primary vertex within  $140 \mu\text{m}$ .

In offline analysis, after reconfirming the trigger cuts with offline quantities, further cuts are imposed on transverse momenta and impact parameters of the two tracks, and on transverse decay length, impact parameter and isolation of the  $B$  candidate. Isolation is defined as  $\frac{p_T(B)}{p_T(B) + \sum p_T}$ , where the sum runs on every other track within a cone of radius 1 in  $\eta$ - $\phi$  space around the  $B$  candidate flight direction. This cut is particularly effective in rejecting combinatoric background. The set of cuts was chosen to maximize the quantity  $S/(S + B)^{1/2}$ , where  $S$  is the number of signal events expected from detailed simulation, and  $B$  is the background estimated by extrapolating the sidebands of the data.

The resulting distribution of invariant mass, with an arbitrarily chosen pion mass assignment to both tracks, shows a clear signal of  $893 \pm 47$  events and  $\sigma = 38 \pm 2 \text{ MeV}/c^2$ , with a peak S/B in excess of 2 (Fig. 1).

Detailed simulation predicts sizeable, closely spaced signals in this mass region from two  $B_d$  modes:  $B_d \rightarrow \pi^+ \pi^-$ ,  $B_d \rightarrow K^+ \pi^-$  and two  $B_s$  modes:  $B_s \rightarrow K^- \pi^+$ ,  $B_s \rightarrow K^+ K^-$ , forming a single unresolved bump. In addition, the  $\Lambda_b \rightarrow p \pi^-, p K^-$  modes might appear as a slight excess around

5.5 GeV/c<sup>2</sup>.

### 3 Measurement of individual modes

The relative contributions to the signal of each  $B_{d,s} \rightarrow h^+h'^-$  component, and the CP asymmetry of the self-tagging  $B_d \rightarrow K^+\pi^-$  mode were measured by means of an unbinned likelihood fit which combines kinematics and PID information on the two tracks. The Likelihood for the  $i^{th}$  event is written as:

$$\mathcal{L}_i = b \cdot \mathcal{L}^{bck} + (1 - b) \cdot \mathcal{L}^{sig}$$

The index *sig* (*bck*) labels the contribution of signal (background), and *b* is the background fraction. The signal likelihood function is  $\mathcal{L}^{sig} = \sum_j f_j \cdot \mathcal{L}_j^{kin} \cdot \mathcal{L}_j^{PID}$ , where the index *j* runs over all possible  $B_{d,s} \rightarrow h^+h'^-$  modes and the parameters *f<sub>j</sub>* are their relative fractions to be determined by the fit.

$\mathcal{L}_j^{kin}$  is in principle a function of the invariant mass of the track pair, with a mode-dependent mass assignment to each outgoing particle. In a rigorous approach<sup>4</sup>, one would then need to write every term in the likelihood (including the background part) as functions of the joint (correlated) distribution of all four possible masses.

In order to simplify the problem, only two variables are used: (1) the invariant mass  $M_{\pi\pi}$  computed with the pion mass assignment to both tracks and (2) a signed momentum imbalance, defined as  $\alpha = (1 - \frac{p_1}{p_2}) \cdot q_1$ , where  $p_1$  ( $p_2$ ) is the smaller (larger) of the track momenta, and  $q_1$  is the charge of the smaller momentum track. It can be shown that the candidate mass calculated with any possible mass assignment to the two tracks can be written to a good approximation as functions of just  $M_{\pi\pi}$  and  $\alpha$ , which therefore provide a compact summary of all available kinematic information (Fig. 2).

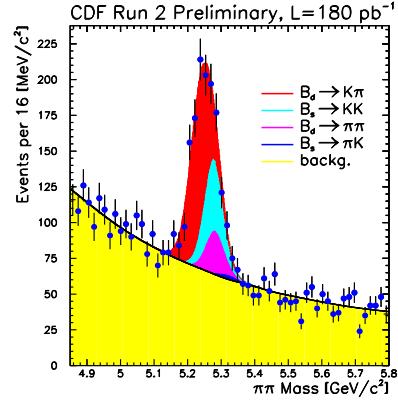


Figure 1.  $M_{\pi\pi}$  distribution of the  $B \rightarrow h^+h'^-$  candidates after all selection cuts. The result of the fit is overlaid.

The kinematic term is then written as:

$$\mathcal{L}_j^{kin} = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2} \left( \frac{M_{\pi\pi} - \mathcal{M}_j(\alpha)}{\sigma} \right)^2} \cdot P_j(\alpha)$$

where the  $\mathcal{M}_j(\alpha)$  are very simple analytical expressions obtained by series expansion; detailed detector simulation shows that they are very accurate within the kinematic range of interest (Fig. 2).  $P_j(\alpha)$  is distribution of  $\alpha$  for each signal mode after the effect of reconstruction cuts, as determined from full simulation and parameterized by a 6<sup>th</sup> order polynomial. The mass resolution  $\sigma$  is set by rescaling simulation predictions to match the observed widths of several other two-body decays ( $D^0 \rightarrow h^+h'^-$ ,  $J/\psi \rightarrow \mu^+\mu^-$  and  $\Upsilon \rightarrow \mu^+\mu^-$ ). The uncertainty in this rescaling is accounted for in the final systematics.

The Likelihood term related to particle identification information is

$$\mathcal{L}_j^{PID} = pdf_j^{PID}(\text{ID}_1, \text{ID}_2, \sigma_1, \sigma_2)$$

with the observable ID carrying information from the specific energy release of the track in the drift chamber gas  $dE/dx_{meas}$ , and is defined as:  $\text{ID} = \frac{\frac{dE}{dx}_{meas} - \frac{dE}{dx}_{exp-\pi}}{\frac{dE}{dx}_{exp-K} - \frac{dE}{dx}_{exp-\pi}}$  where  $dE/dx_{exp-K}$  ( $dE/dx_{exp-\pi}$ ) is the expected

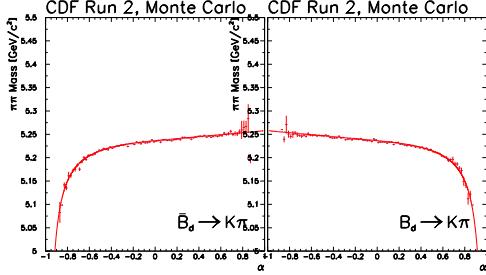


Figure 2. (Left)  $M_{\pi\pi}$  vs  $\alpha$  for  $\bar{B}_d \rightarrow \pi^+ K^-$ , compared to the first-order expression:  $M_{\pi\pi}^2 = M_{B_d^0}^2 + (2 - \alpha)(m_\pi^2 - m_K^2)$ . (Right) Same for  $B_d \rightarrow \pi^- K^+$ .

value in the kaon (pion) hypothesis. The expected value of ID is then by construction equal to 0 for a pion, 1 for a kaon. This parameterization allows using a single observable for both the pion and kaon terms.

The  $pdf^{PID}$  function is a non-factorizable distribution of two correlated Gaussians, with track-dependent resolutions  $\sigma_1, \sigma_2$ , and a fixed correlation  $\sigma_{12}$ , determined from data. The distributions of resolutions have been checked to be equal for all modes<sup>4</sup>. The response of the drift chamber has been calibrated with a large sample of  $D^0 \rightarrow K\pi$  decays from the same trigger, with their sign tagged by the presence of a  $D^{*\pm}$ . The correlation between the measured  $dE/dx$  of two tracks in the same event, due to time-dependent fluctuations of the drift chamber gain, has been measured with the same sample. The average  $K/\pi$  separation was measured to be  $1.4\sigma$  in the kinematical range of interest. This moderate resolution is however sufficient to provide a statistical separation between K and  $\pi$  which is 60% of what a perfect PID would provide. The uncertainty on the calibrations, and the effect of small unmodeled non-Gaussian tails have also been evaluated from data and included in the final systematic uncertainty.

The background is described by  $\mathcal{L}^{bck} = \mathcal{L}_{bck}^{kin} \cdot \mathcal{L}_{bck}^{PID}$ , with the kinematic term:

$$\mathcal{L}_{bck}^{kin} = P_{bck}(\alpha) \cdot (e^{c_0 + c_1 \cdot M_{\pi\pi}} + c_2)$$

where  $P_{bck}(\alpha)$  is the distribution of  $\alpha$  for background events, obtained from sidebands of real data and parameterized as a 6<sup>th</sup> degree polynomial. The  $c_i$  are free parameters in the fit. A few alternative parameterizations of the background mass spectrum have been tested, and the corresponding parameter variations included in the systematics.

The PID term for the background is similar to the signal, and assumes that only pions and kaons are present, with each track having an independent probability  $f_\pi$  to be a pion. The pion fractions  $f_\pi$  are left free in the fit to vary independently in three mass regions (left, under, and right of the signal peak).

The complete likelihood fit has been tested on MonteCarlo samples, and showed gaussian pulls on all variables with unit sigma and negligible biases.

#### 4 Efficiency corrections

To extract relative branching fractions from the raw fit results it is necessary to correct for different efficiency of the selection on each decay. Most corrections are obtained from detailed detector simulation; exceptions are the efficiency of the  $B$  isolation cut (only affecting  $B_d/B_s$  ratios), the difference in efficiency of the trigger track processor for kaons and pions due to their different energy release in the drift chamber gas, and the charge asymmetry. These three effects are not reliably simulated, and have been measured from real data. A systematic has been added for possible differences between  $B_d$  and  $B_s$  momentum spectra<sup>11</sup>, that are treated as equal in the simulation.

Isolation efficiency has been measured as a function of  $B$  transverse momentum from fully reconstructed samples of  $B_s \rightarrow J/\psi\phi$ ,  $B_s \rightarrow D_s\pi$ ,  $B_d \rightarrow J/\psi K^*$ ,  $B_d \rightarrow D^-\pi^+$ . The difference in trigger efficiency for pions and kaons has been measured from an unbiased sample of pions and kaons from charm decays. The momentum dependent charge

asymmetry of CDF tracking has been measured on large samples of inclusive tracks and on  $K_s \rightarrow \pi^+ \pi^-$  decays<sup>5</sup>, and used to correct our measurement of direct  $A_{CP}$ . The size of this correction is about 1% and its relative uncertainty ( $\pm 25\%$ ) is included in the final systematics.

The resulting total efficiency varies between modes by less than 12%.

The total systematic uncertainties are dominated by uncertainties in  $dE/dx$  calibration and efficiency of the isolation cut. Both uncertainties are due to statistical uncertainties in the calibrations samples, and are therefore expected to decrease with sample size.

## 5 Results

The ratio of the  $B_d$  modes:

$$\frac{BR(B_d \rightarrow \pi^\pm \pi^\mp)}{BR(B_d \rightarrow K^\pm K^\mp)} = 0.24 \pm 0.06 \pm 0.05$$

is in good agreement with the current world average<sup>6</sup>:  $0.25 \pm 0.025$ . The direct CP asymmetry is:

$$\frac{N(\overline{B}_d^0 \rightarrow K^- \pi^+) - N(B_d^0 \rightarrow K^+ \pi^-)}{N(\overline{B}_d^0 \rightarrow K^- \pi^+) + N(B_d^0 \rightarrow K^+ \pi^-)} = -0.04 \pm 0.08 \pm 0.006$$

which is compatible both with zero, and with the measurements performed by BaBar and Belle collaborations<sup>8</sup>.

For the  $B_s$  sector:

$$\frac{f_s \cdot BR(B_s \rightarrow K^\pm K^\mp)}{f_d \cdot BR(B_d \rightarrow K^\pm \pi^\mp)} = 0.50 \pm 0.08 \pm 0.07$$

Since this is a CP eigenstate, it is possible for its lifetime to be different from the average  $B_s$  lifetime measured from semileptonic modes. The above result is obtained under the assumption that  $\Gamma_s = \Gamma_d$ , the  $B_s \rightarrow K^+ K^-$  mode is dominated by the short-lived component, and that  $\Delta\Gamma_s/\Gamma_s = 0.12 \pm 0.06$  (the latter uncertainty is included in the quoted

systematics). We also quote:

$$\frac{f_d \cdot BR(B_d \rightarrow \pi^\pm \pi^\mp)}{f_s \cdot BR(B_s \rightarrow K^\pm K^\mp)} = 0.48 \pm 0.12 \pm 0.07$$

From the above numbers, the absolute BR can be obtained<sup>10</sup>:

$$BR(B_s \rightarrow K^\pm K^\mp) = 34.3 \pm 5.5 \pm 5.2 \cdot 10^{-6}$$

This is almost twice the BR of  $B_d \rightarrow K^\pm \pi^\mp$  which differs only in the spectator quark, in agreement with recent calculations of flavor-SU(3) breaking<sup>7,3</sup>. This result will hopefully be a useful input for theoretical models of charmless decays. The large yield ( $\approx 230$  events in current sample) also offers an interesting opportunity for a measurement of  $\Delta\Gamma_s$  without the need for an angular analysis.

No evidence is found for the other  $B_s$  decay for which a sizeable BR is expected, and a limit<sup>12</sup> is set:

$$\frac{f_s \cdot BR(B_s \rightarrow K^\pm \pi^\mp)}{f_d \cdot BR(B_d \rightarrow K^\pm \pi^\mp)} < 0.11 \text{ @ 90\% C.L.}$$

This translates to<sup>10</sup>:

$$BR(B_s \rightarrow K^\pm \pi^\mp) < 7.5 \cdot 10^{-6} \text{ @ 90\% C.L.}$$

which is close to the lower end of current expectations. In addition to the above, rarer modes (BR:  $10^{-8}$  to  $10^{-7}$ ) dominated by penguin annihilation and exchange diagrams have been searched for by adding their expected contributions to the Likelihood. In each case, the fit parameters changed by a negligible amount, and no evidence was found for those modes. The following limits<sup>12</sup> are set:

$$\frac{BR(B_d \rightarrow K^\pm K^\mp)}{BR(B_d \rightarrow K^\pm \pi^\mp)} < 0.17 \text{ @ 90\% C.L.}$$

or<sup>10</sup>:

$$BR(B_d \rightarrow K^\pm K^\mp) < 3.1 \cdot 10^{-6} \text{ @ 90\% C.L.}$$

The current best limit in this mode is<sup>9</sup>  $0.6 \cdot 10^{-6}$ .

$$\frac{BR(B_s \rightarrow \pi^\pm \pi^\mp)}{BR(B_s \rightarrow K^\pm K^\mp)} < 0.10 \text{ @ 90\% C.L.}$$

This is derived under the assumption that both modes have the same average lifetime. This translates<sup>10</sup> to:

$$BR(B_s \rightarrow \pi^\pm \pi^\mp) < 3.4 \cdot 10^{-6} \text{ @ 90\% C.L.}$$

which is a substantial improvement over the previous best limit<sup>9</sup> of  $1.7 \cdot 10^{-3}$ .

The same data have also been used in a separate search for the charmless decay  $\Lambda_b^0 \rightarrow p\pi^-, pK^-$ , by counting the number of events found in the search window  $5.415 - 5.535 \text{ GeV}/c^2$ . The choice of the window and the cuts have been optimized for maximum sensitivity<sup>13</sup>. No evidence for signal is found, and a Bayesian upper limit, based on uniform prior, is obtained at 90% credibility:  $BR(\Lambda_b^0 \rightarrow p\pi^-/pK^-) \leq 22 \times 10^{-6}$ .

This is an improvement over the previous limit:  $BR(\Lambda_b^0 \rightarrow p\pi^-, pK^-) \leq 50 \times 10^{-6}$  at 90%CL<sup>14</sup>. Predictions<sup>15</sup> lie in the range  $2 - 3 \times 10^{-6}$ . Improved sensitivity is expected in the future with inclusion of PID information for the proton.

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